The role of astrometry in the study of exoplanets

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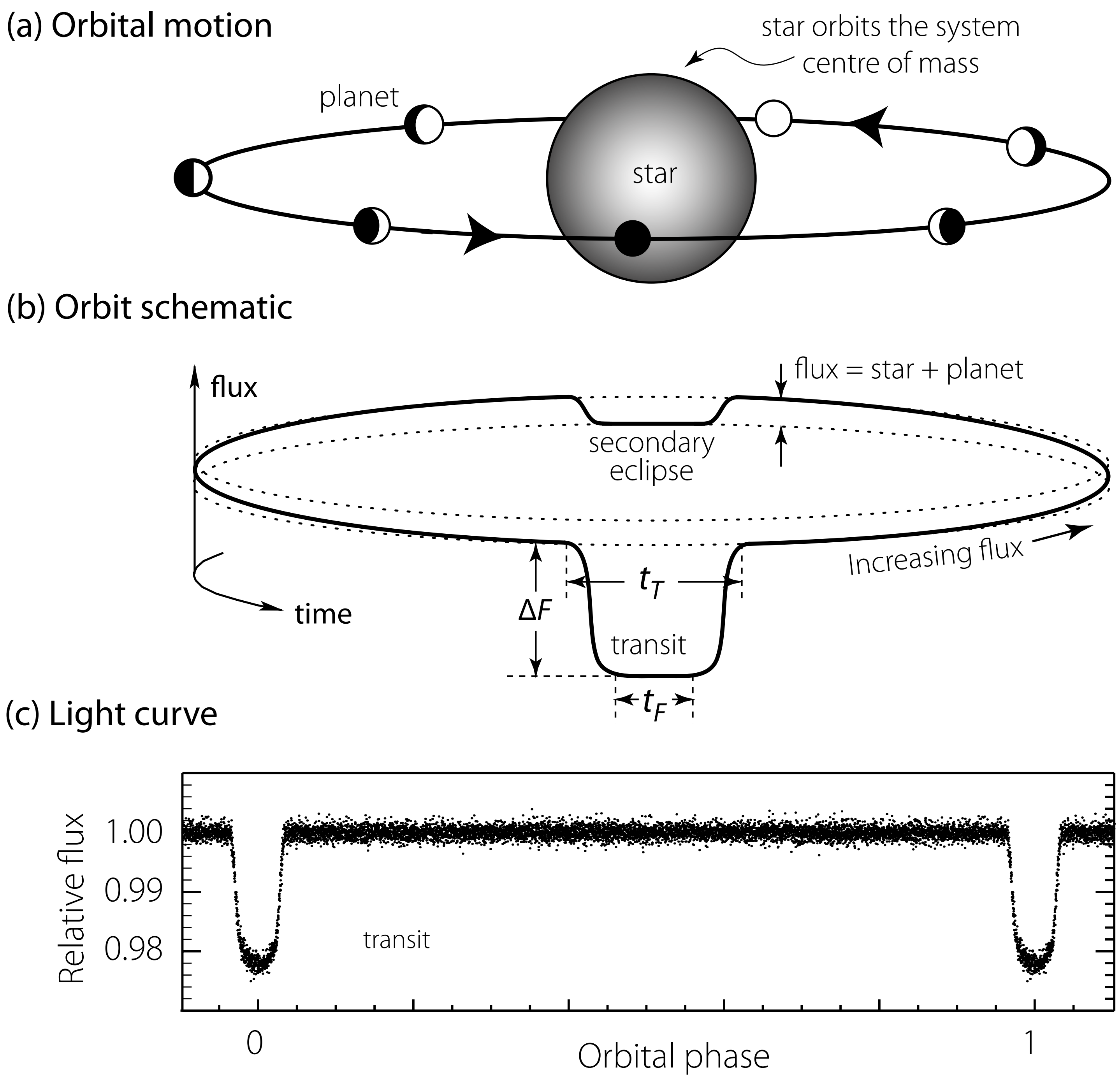
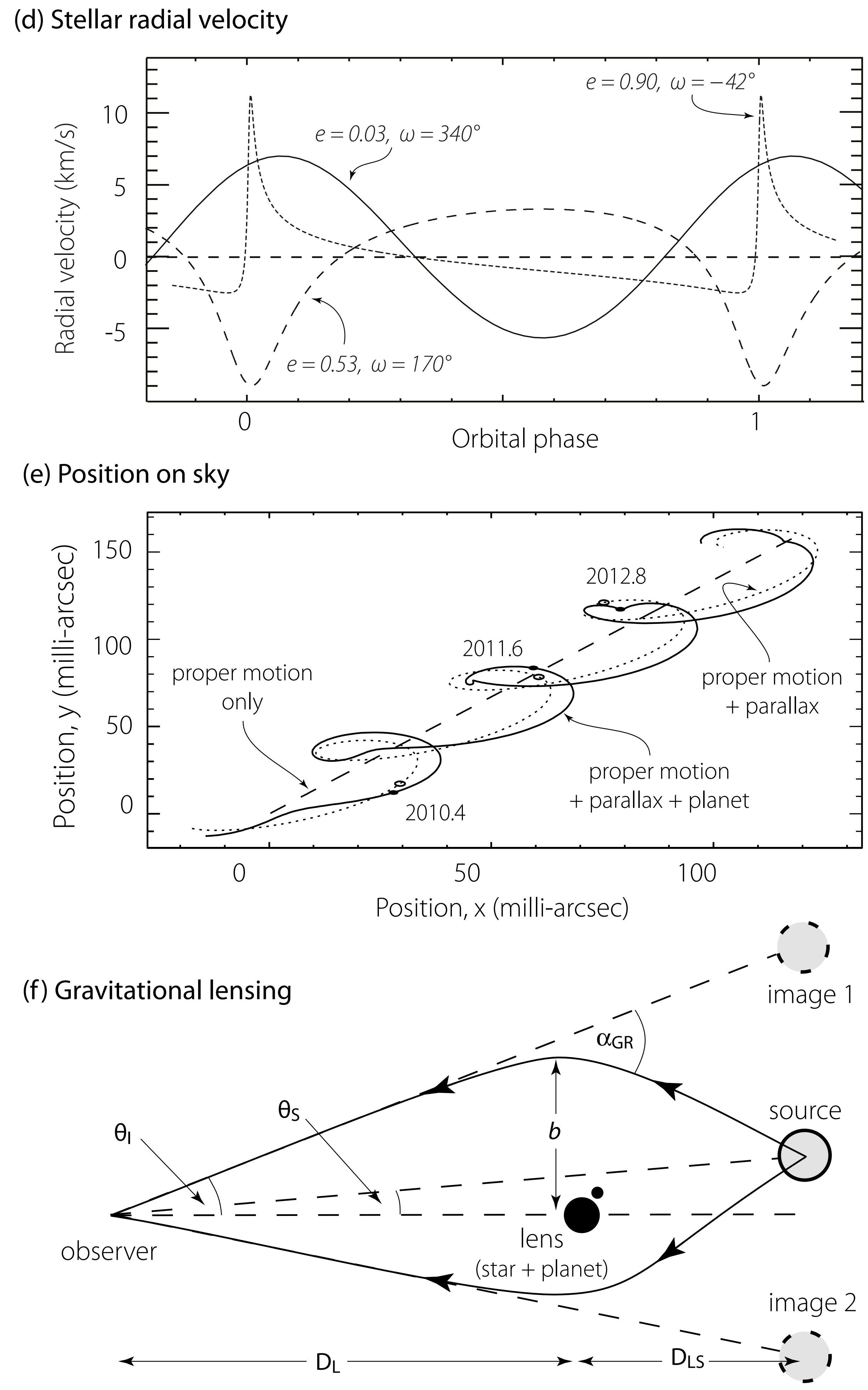
(Erlangen, 8-10 October 2014)

“It is almost certain that there is some form of vegetation on Mars”

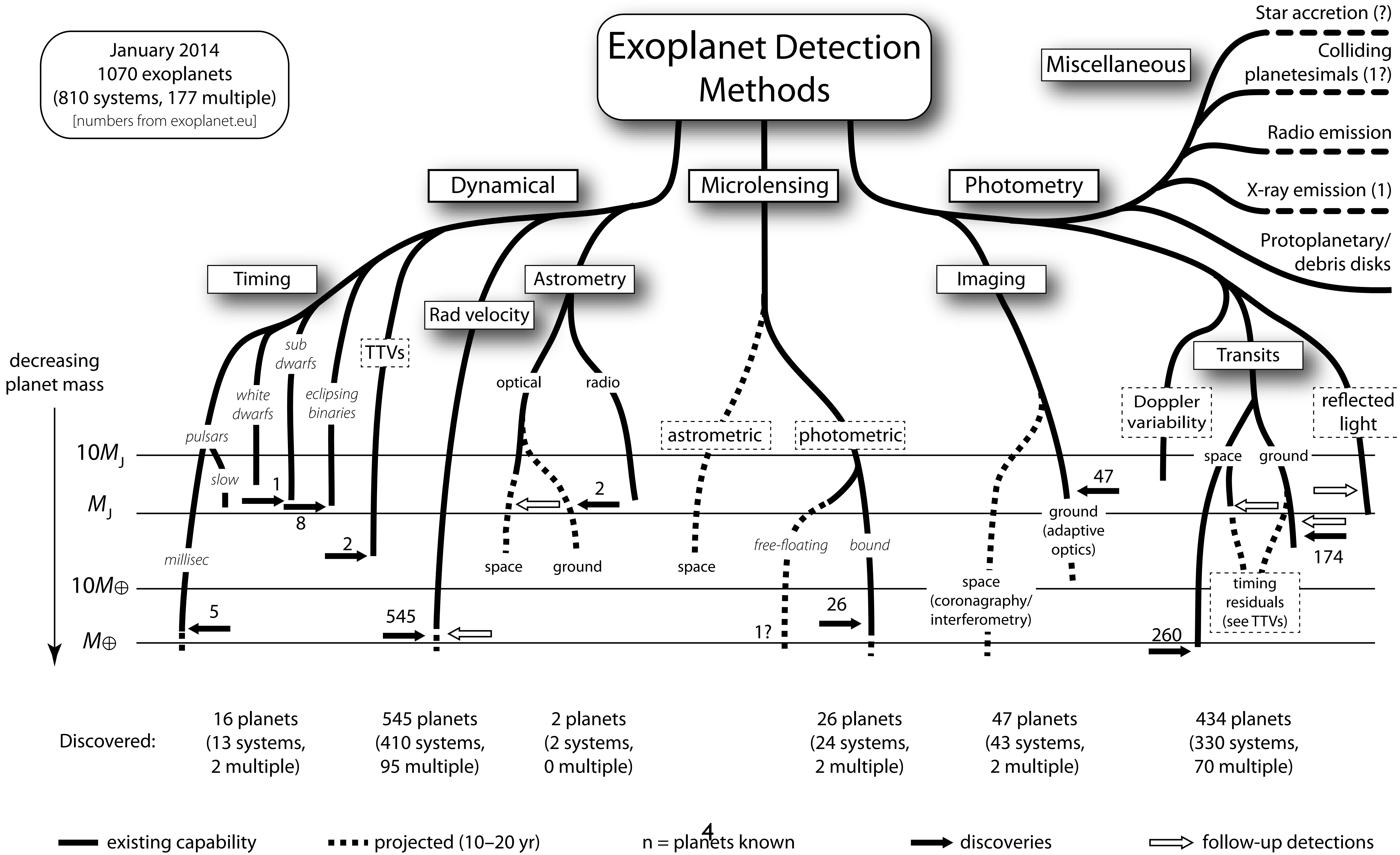
Spencer Jones, 1940

Summary of detection methods





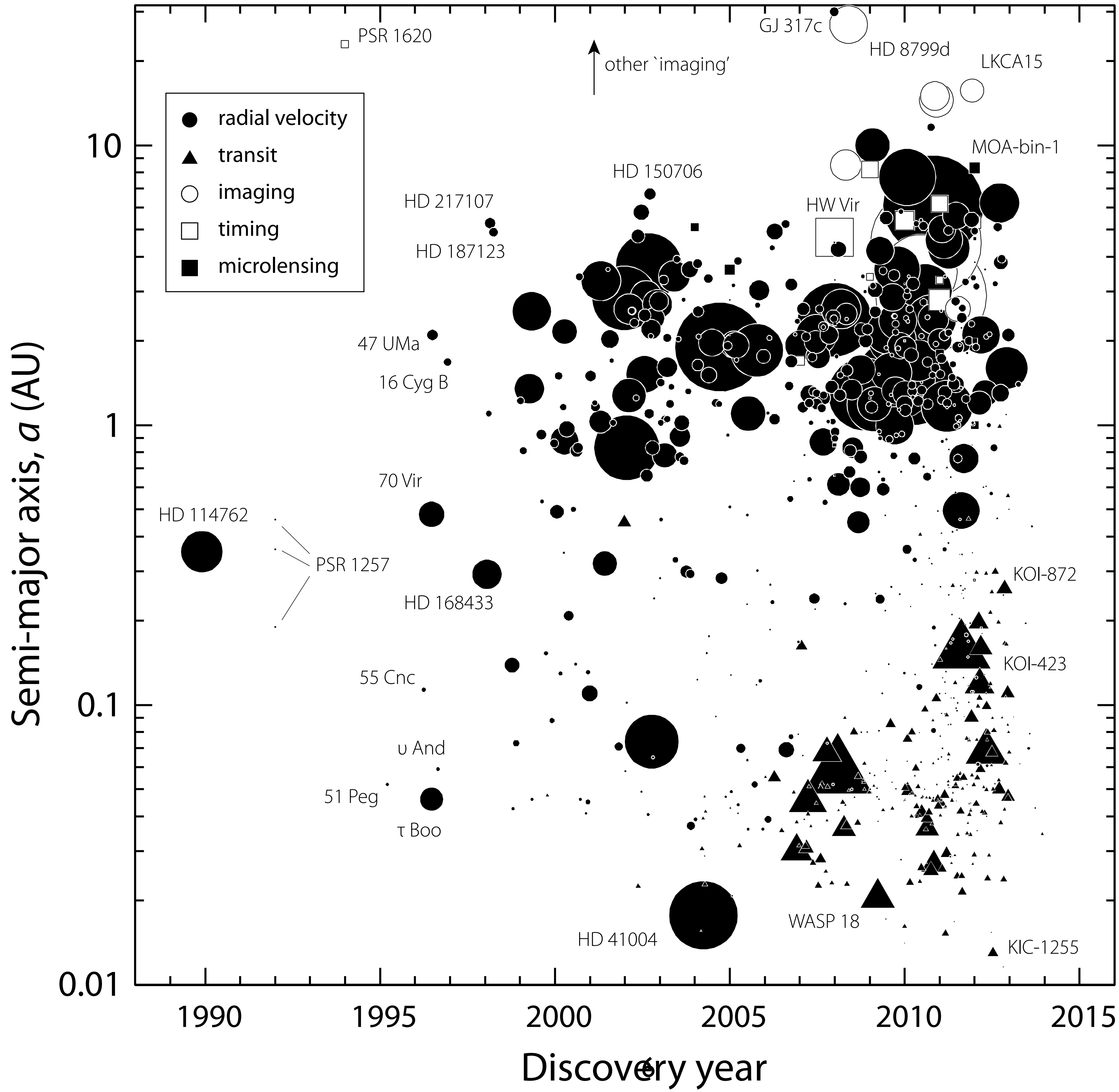
Astrometry in the context of exoplanet detection/characterisation



The 'tragic history' of astrometric planet detection

- Jacob (1855) 70 Oph: orbital anomalies made it *'highly probable'* that there was a *'planetary body'*; supported by See (1895); orbit shown as unstable (Moulton 1899)
- Holmberg (1938): from parallax residuals... *`Proxima Centauri probably has a companion'* of a few Jupiter masses
- Reuyl & Holmberg (1943) 70 Oph: planetary companion of ~10 M_J
- Strand (1943) 61 Cyg: companion of ~16 M_J
- lengthy disputes about planets around Barnard's star: van der Kamp (1963, 1982)
- similarly for Lalande 21185 (e.g. Lippincott 1960)
- Pravdo & Shaklan (2009) vB10 with Palomar-STEPS, later disproved (Bean 2010)
- Muterspaugh+ (2010) HD~176051, only current detection: *'may represent either the first such companion detected, or the latest in the tragic history of this challenging approach.'*
- early discussions of space astrometry/Hipparcos exoplanet capabilities:
    - Couteau & Pecker (1964), Gliese (1982)

The accelerating pace of discovery…



Distances and space motions

Distances and motions

Examples:

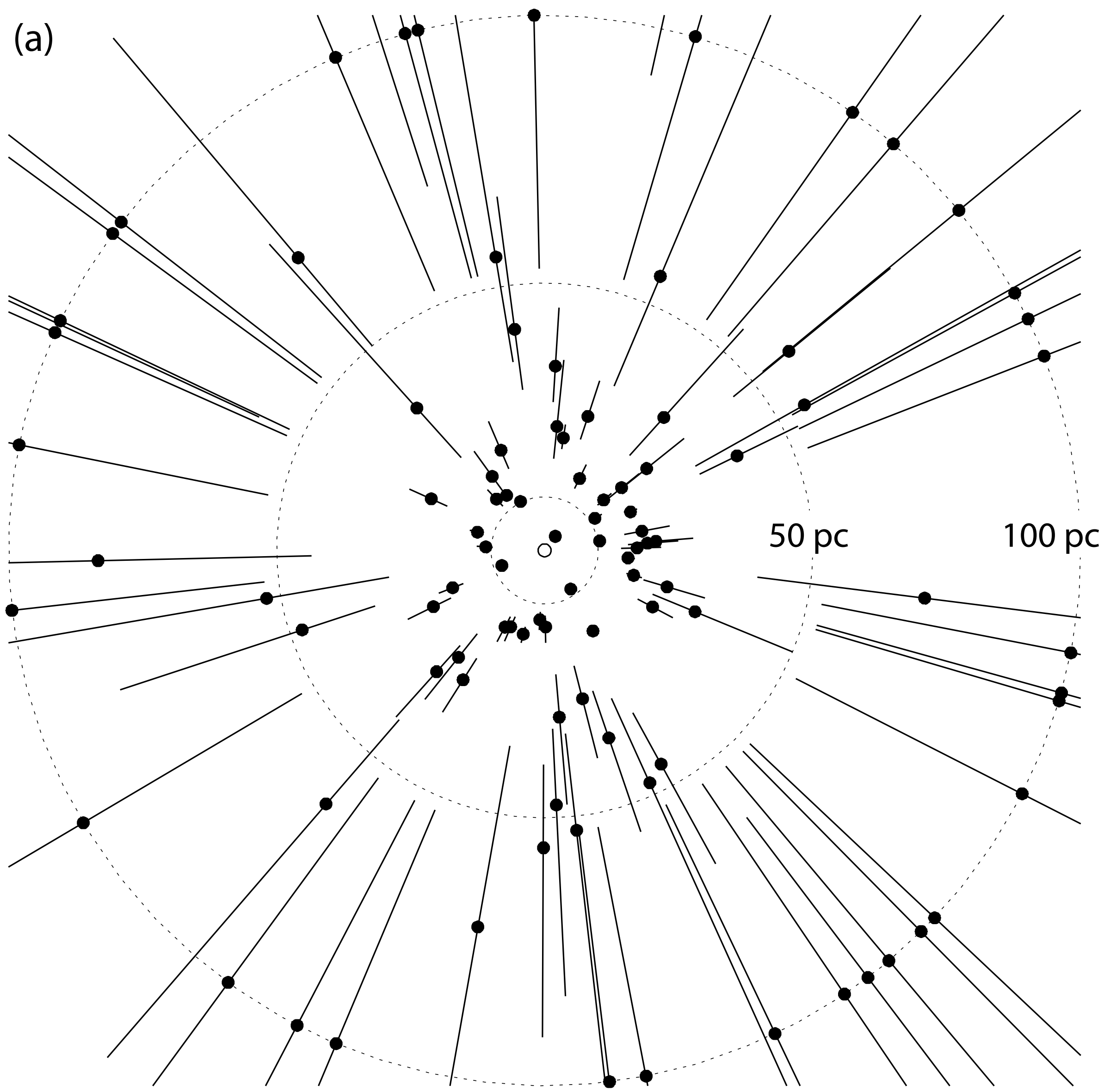
- distances provide stellar parameters
  - e.g. transit planet diameters $\propto$ stellar diameters
- verification of seismology models for *M*, *R*
- proper motions characterise population(s)

  e.g. HIP 13044 low-metallicity Galactic halo stream (Helmi+1999, Setiawan+2010)
- Galactic birthplace based on metallicity-age

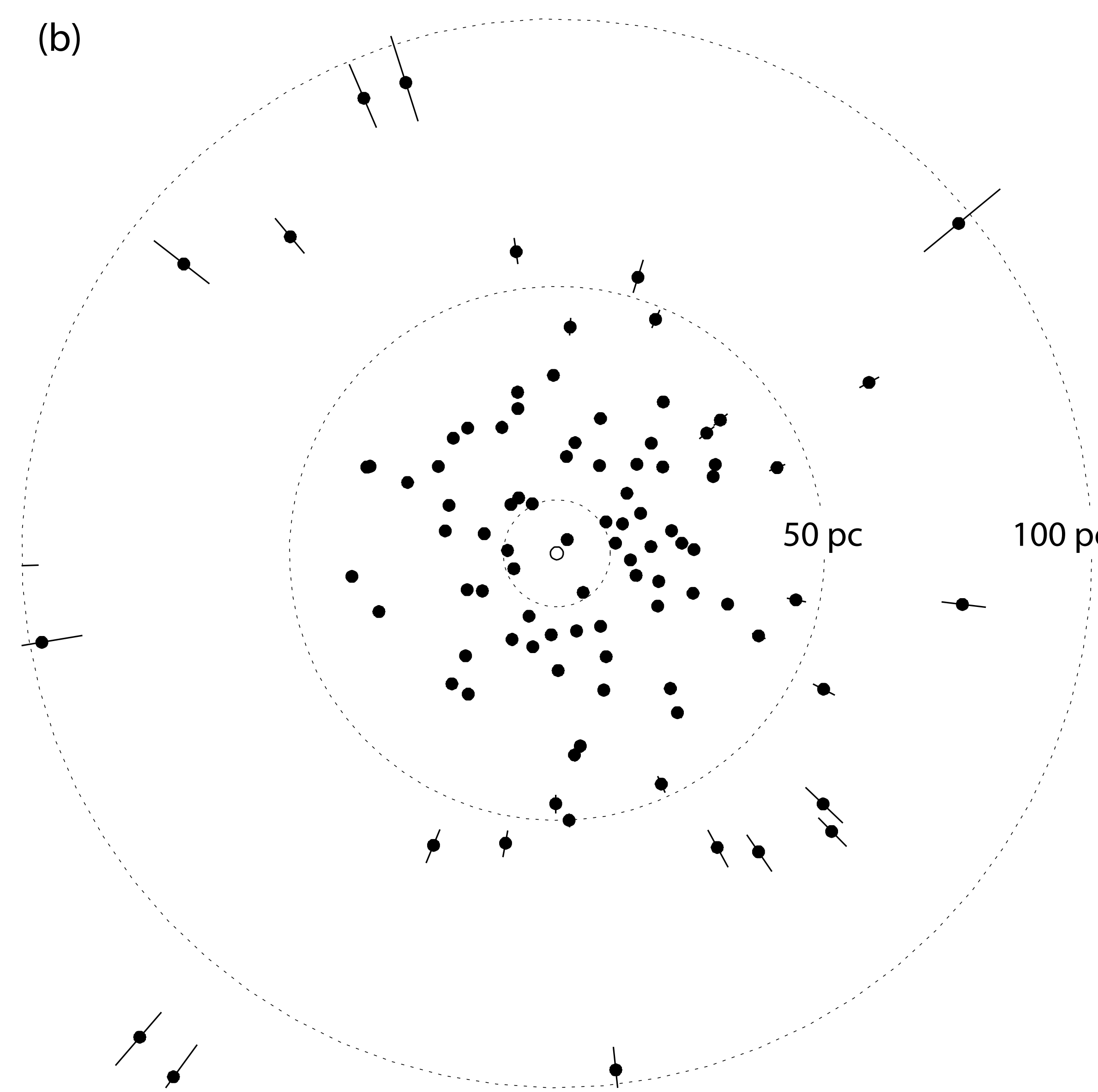
  e.g. Wielen (1996) inferred that the Sun's birthplace was at R=6.6 kpc

Hipparcos distances to exoplanet host stars

100 brightest radial velocity host stars (end 2010)
(versus RA, independent of dec)

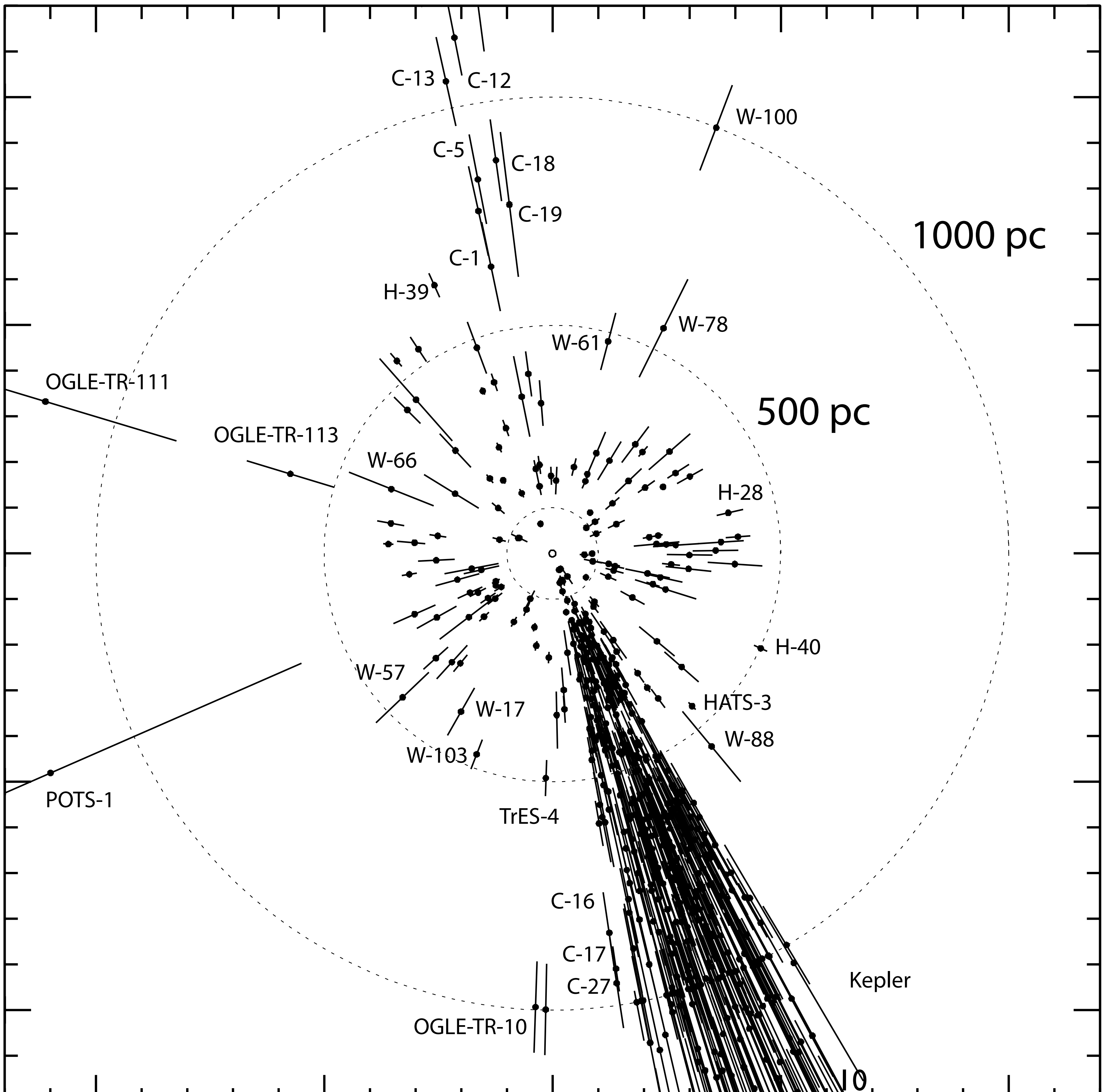


ground-based: van Altena et al (1995)
(unknown assigned π = 10±9 mas)



Hipparcos parallaxes

Gaia distances to exoplanet host stars



Transit host stars only

1129 transiting planets
(2014 May 1)

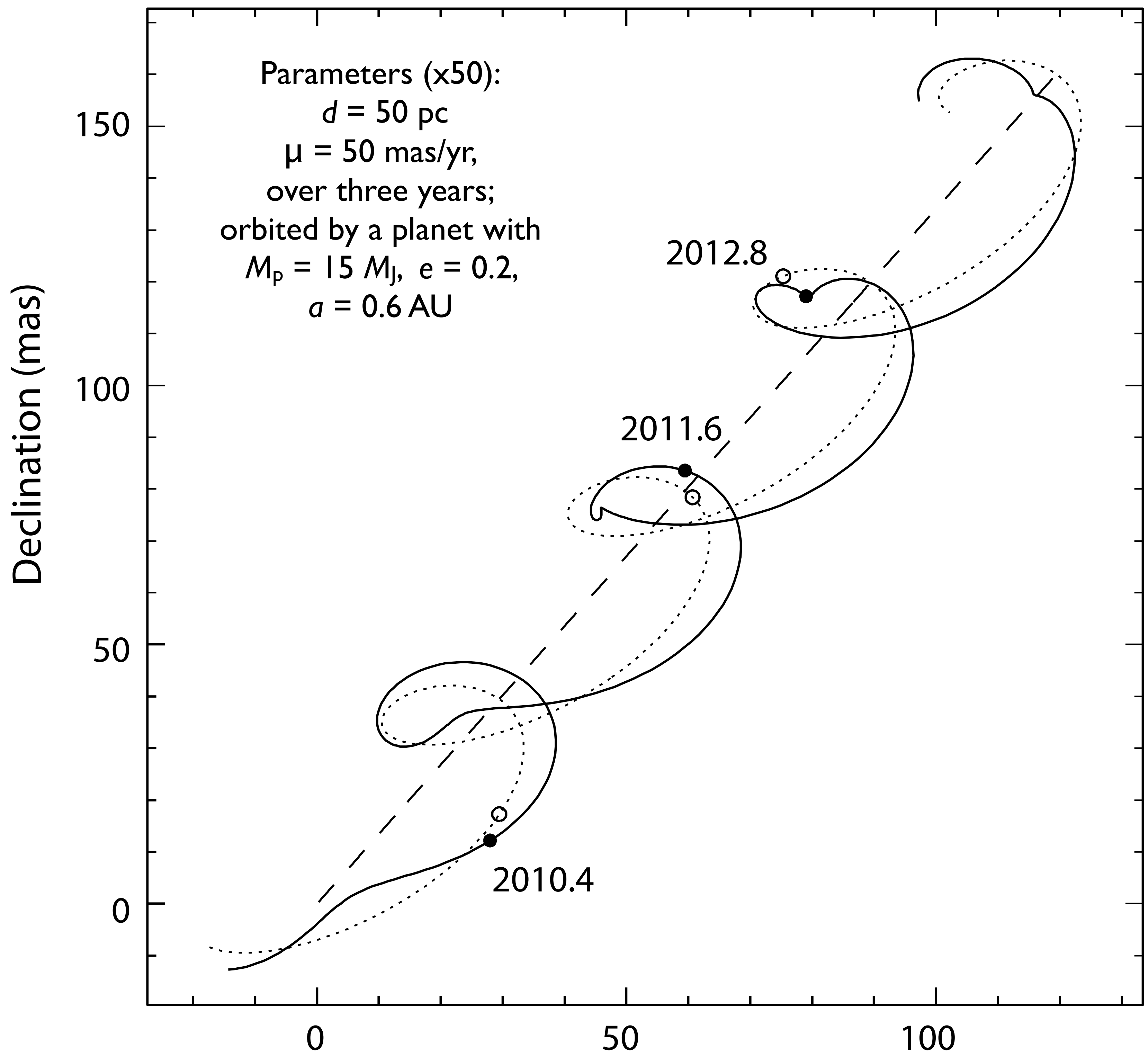
There are:
- 582 distinct host stars
- 188 Hipparcos distances
- 366 Kepler from $K-M_K$ median ~670pc
- 28 placed at 1 kpc

Principles of Gaia astrometric detections

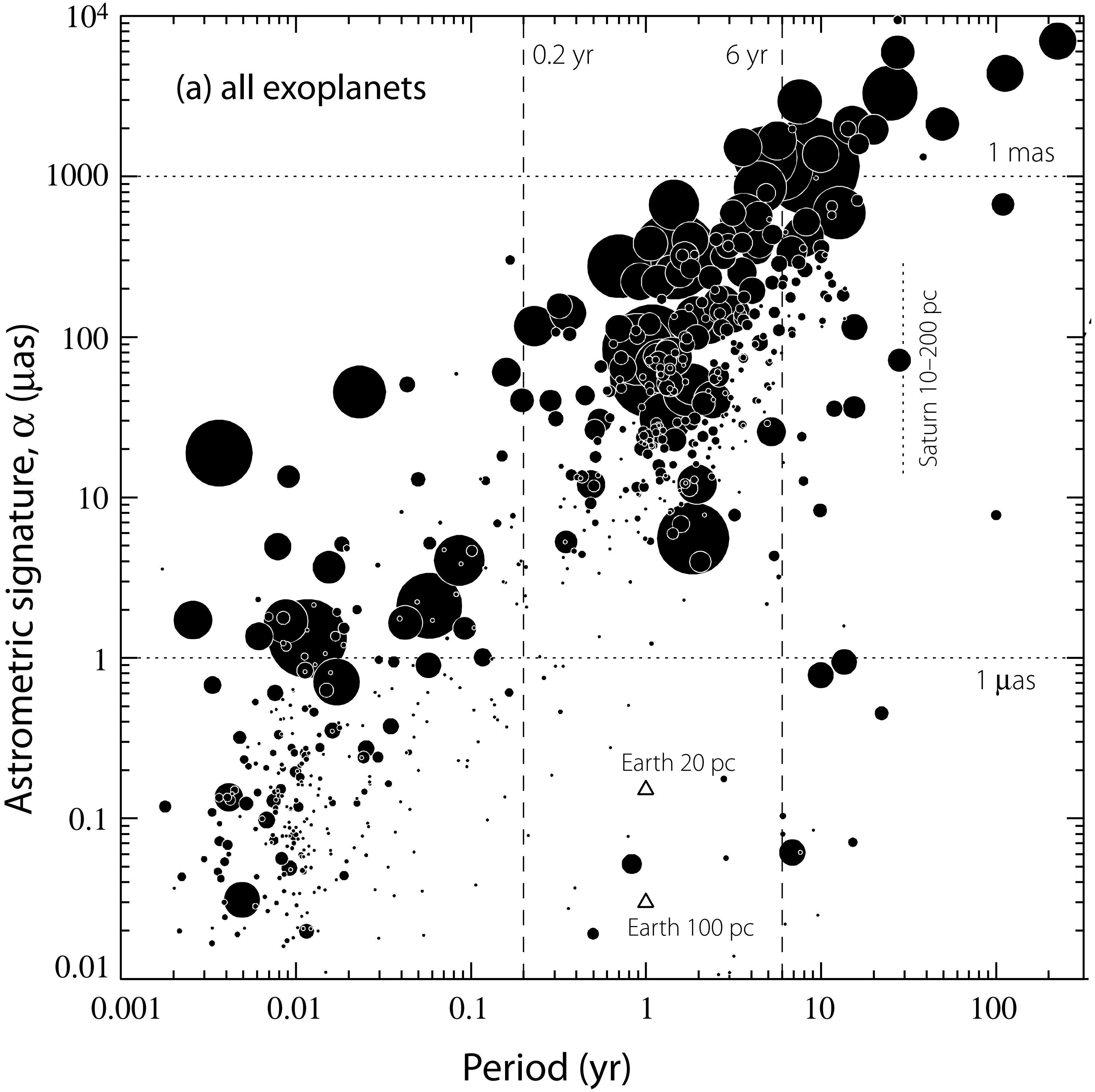
Discovery from 'astrometric signature'

Unseen planets perturb the photocentre, which moves with respect to the barycentre (as for Doppler measures)

and provides *M* directly (not simply *M* sin *i*)



Astrometric signature

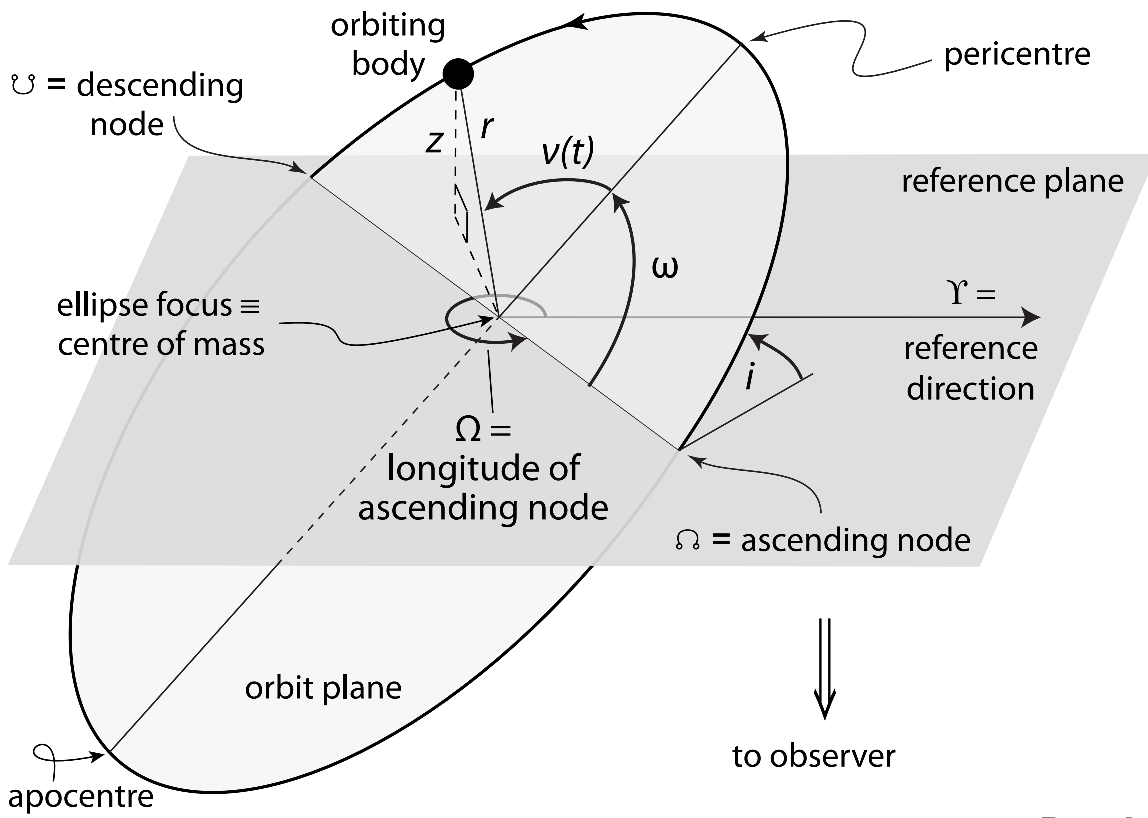


$$\alpha = \frac{M_p}{M_\star + M_p} a \simeq \frac{M_p}{M_\star} a$$

$$\equiv \left(\frac{M_p}{M_\star}\right)\left(\frac{a}{1\ \mathrm{AU}}\right)\left(\frac{d}{1\ \mathrm{pc}}\right)^{-1} \ \mathrm{arcsec}$$

Hipparcos astrometry
is marginal for detection
(and mass determination)

Direct access to planet mass



Keplerian orbit in 3d determined by 7 parameters:
a, e: specify size and shape
P: related to *a* and masses (Kepler's 3rd law)
t_p: the position along orbit at some reference time
i, Ω,ω: represent projections wrt observer

Radial velocity measures:
- cannot determine Ω,
- only determine the combination *a* sin *i*
- only determine $M_p \sin i$ if M_* can be estimated
- cannot determine Δ*i* for multiple planets

All 7 parameters <u>are</u> determinable by astrometry (±180° on Ω). Conceptually:
- *xy(t)* yields max and min angular rates, and hence the line of apsides (major axis)
- then appeal to Kepler's third law fixes the orbit inclination

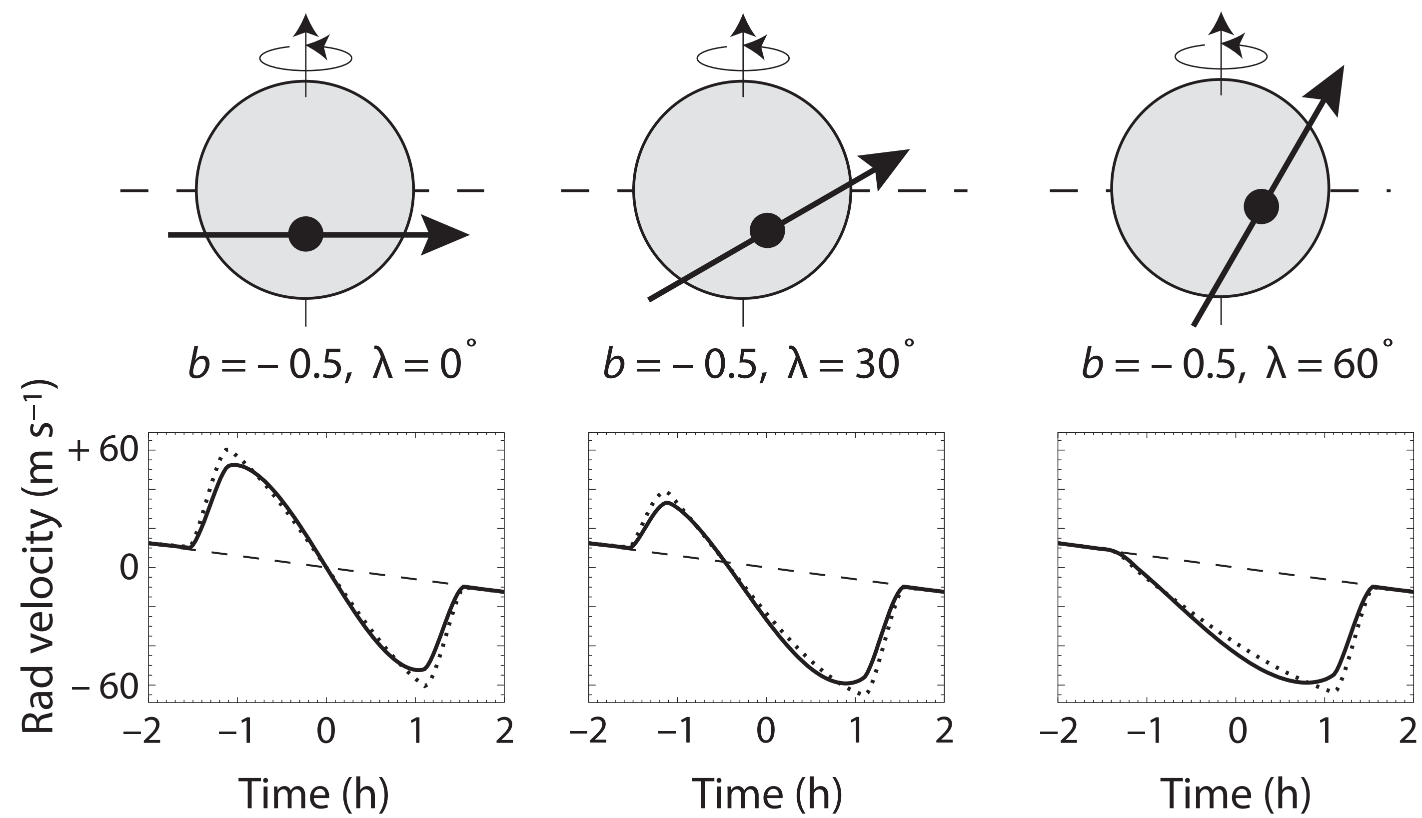
Coplanarity of orbits and transit geometry

Importance of Δi

- $\Delta i \sim 0$ in the solar system
- various evidence that this is not necessarily the rule in exoplanets:

(1) long-term dynamical stability (via numerical integrations) ⇒ some cannot be coplanar

(2) Rossiter-McLaughlin effect used to measure the (sky projection) of the orbital and stellar rotation axes indicates that many orbits are misaligned wrt stellar equator (some retrograde)



(3) models of formation and evolution admit the possibilities of: (a) asymmetric protoplanetary infall; (b) gravitational scattering during the giant impact stage of protoplanetary collisions; (c) Kozai resonance/migration in which L_z is conserved, and hence i and e can be 'traded' (explains high e in triple systems, and hot Jupiters when combined with tidal friction)

$$L_z = \sqrt{(1-e^2)}\cos i$$

Number of Gaia exoplanet detections

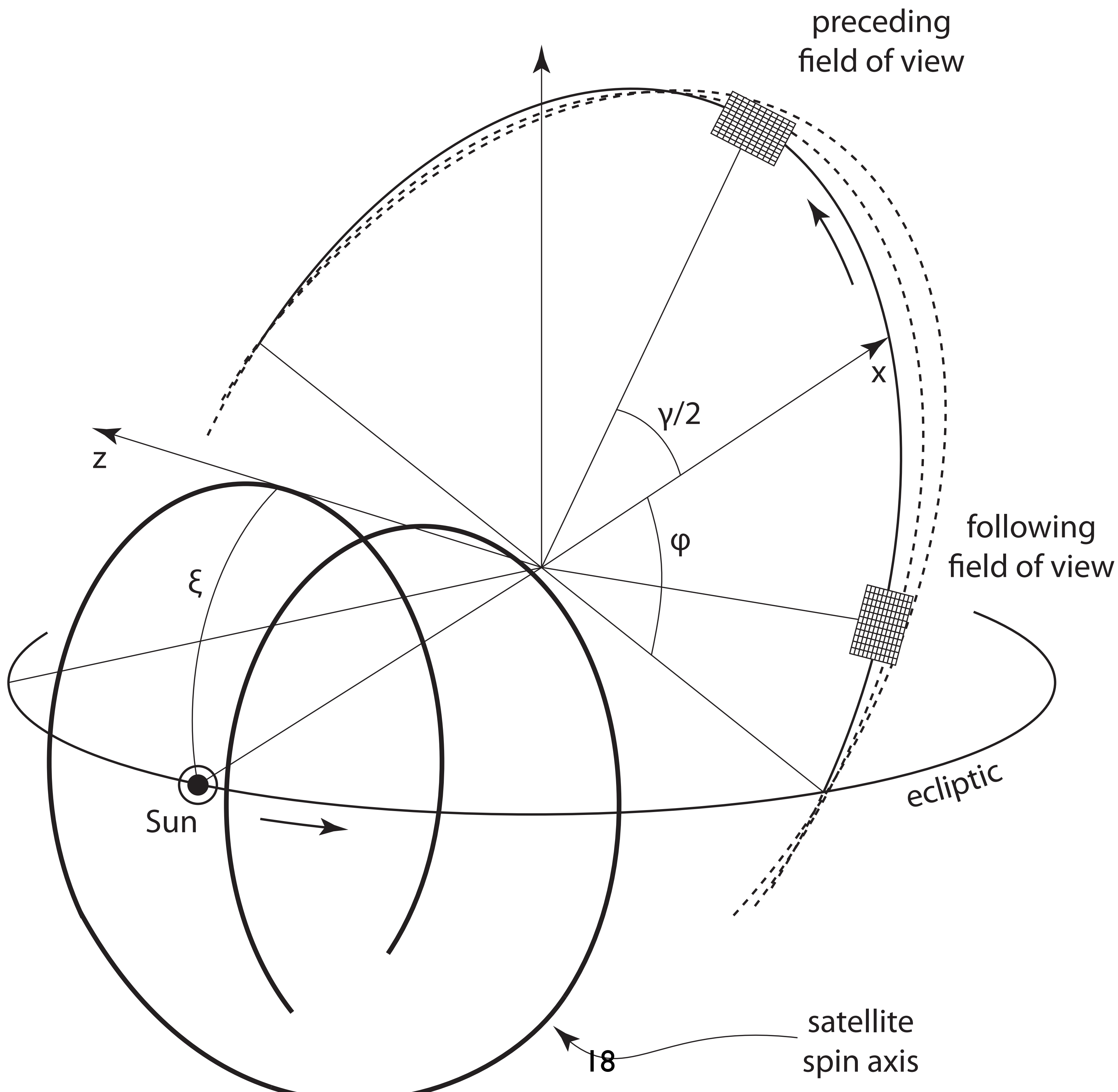
(Perryman, Hartman, Bakos, Lindegren 2014, ApJ submitted)

- based on:
  1. latest accuracies for Gaia: along-scan error versus magnitude

     (but with uncertainties on attitude jitter, bright star performance, etc)
  2. Galaxy population synthesis model: TRILEGAL (Girardi et al 2012)
  3. exoplanet occurrence frequencies versus stellar type, mass, etc

     (but still highly simplified for binary stars, multiple massive planets, etc)
  4. detailed observational model (field-of-view crossings) versus sky position
  5. planet detectability dependent on number and distribution of field-of-view crossings (not just the S/N of a single crossing)

Gaia sky scanning



1. Gaia accuracy

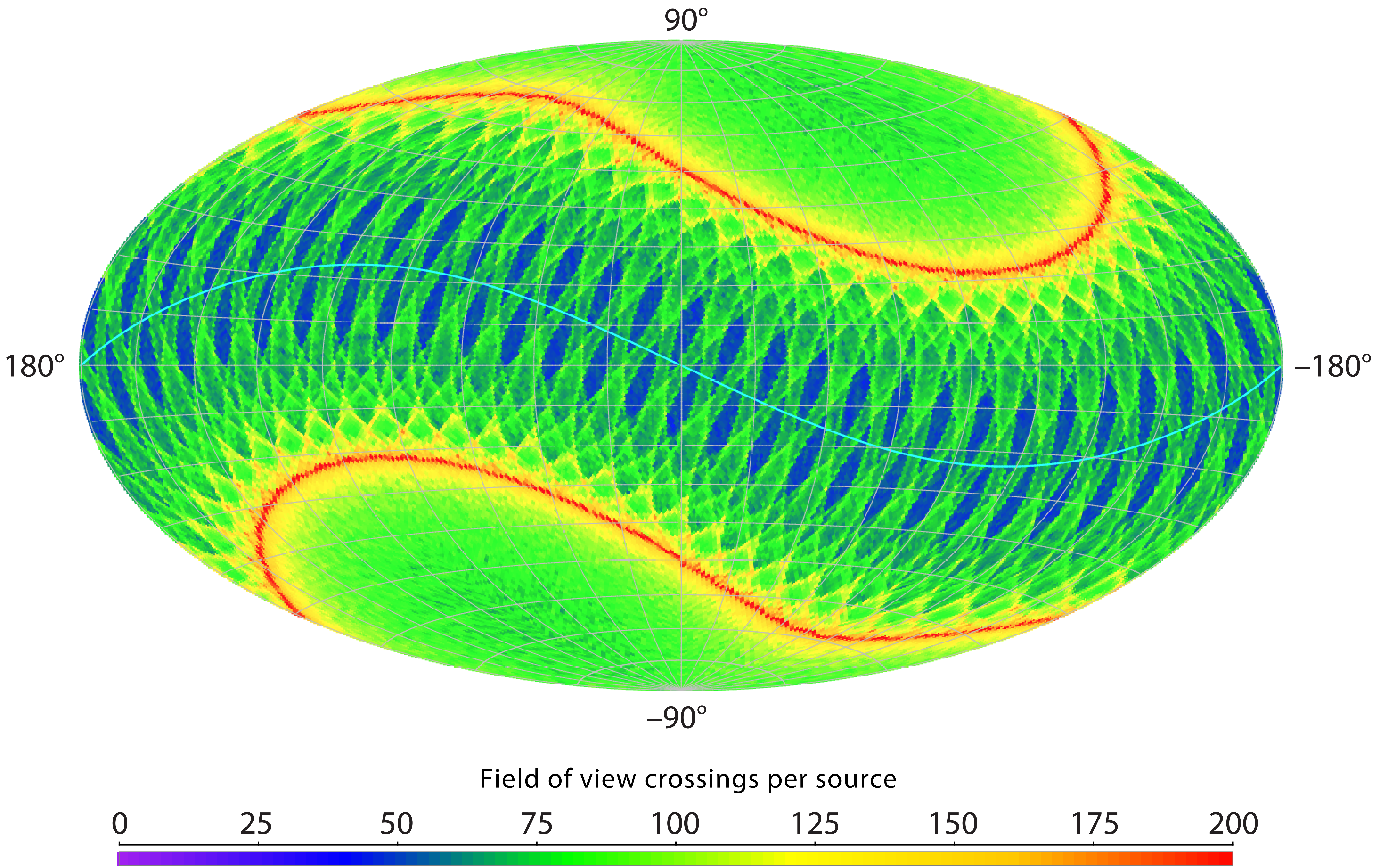
z: relative number of photons

σ_η = centroiding accuracy per CCD

σ_{FOV} = along-scan accuracy per FOV crossing

σ_{pos} = sky-averaged positional error

G (mag)	z	σ_η (μas)	$\sigma_{\rm fov}$ (μas)	$\sigma_{\rm pos}$ (μas)
6	0.063	57.8	34.2	7.7
7	0.063	57.8	34.2	7.7
8	0.063	57.8	34.2	7.7
9	0.063	57.8	34.2	7.7
10	0.063	57.8	34.2	7.7
11	0.063	57.8	34.2	7.7
12	0.063	57.8	34.2	7.7
13	0.158	91.7	41.6	9.4
14	0.398	145.4	56.1	12.7
15	1.000	230.9	82.0	18.5
16	2.512	367.5	125.7	28.4
17	6.310	588.9	198.3	44.8
18	15.849	958.1	320.6	72.5
19	39.811	1612.8	538.4	121.7
20	100.000	2898.3	966.5	218.4


90°
180°
−180°
−90°
Field of view crossings per source
0
25
50
75
100
125
150
175
200

2. Galaxy model

- used the population synthesis model TRILEGAL:
  - components: halo, thick/thin disks, bulge, disk extinction layer
  - theoretical stellar LF derived from evolutionary tracks (as a function of absolute magnitude, position, and photometric passband) using IMF, SFR, and AMR
  - can retain stellar properties (mass, age, metallicity, Teff, etc)
  - we interpolated 1deg fields in 10 deg steps of long/latitude
  - magnitude limit: $r < 17.5$ mag
  - total number of stars (including binaries): 260 million

3. Assumed planet occurrences

- binary stars: secondaries ignored
- host star mass/metallicity: Johnson et al (2010)
- planet mass and period:

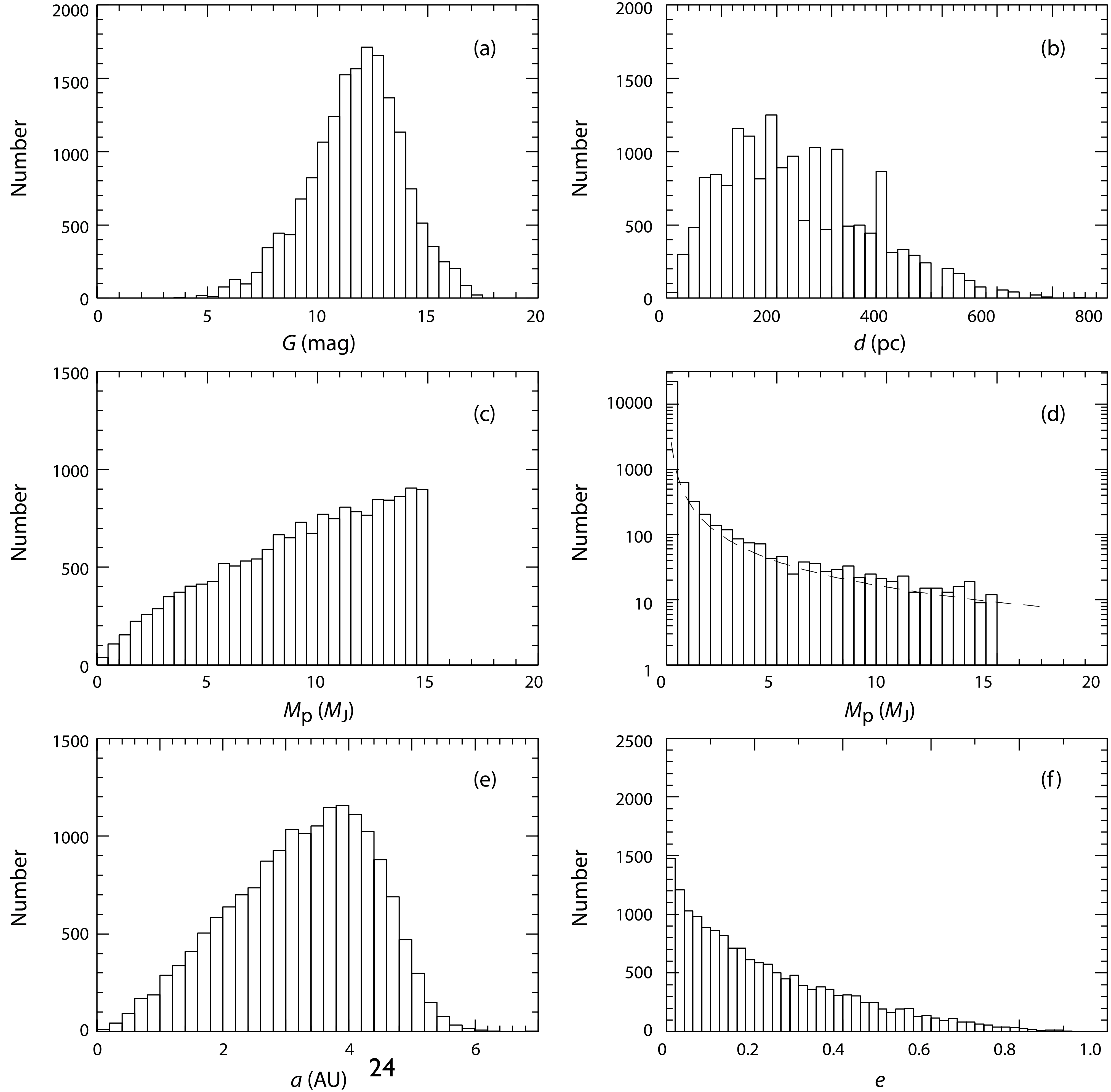
Class	R_p ($R_\oplus$)	M_p (M_J)	P	f	Reference
Earth	0.8–1.25	0.002–0.007	0.8– 85 d	0.1840	Fressin et al. 2013
super Earth	1.25–2	0.007–0.018	0.8–145 d	0.2960	Fressin et al. 2013
small Neptune	2–4	0.018–0.033	0.8–245 d	0.3090	Fressin et al. 2013
large Neptune	4–6	0.033–0.077	0.8–418 d	0.0318	Fressin et al. 2013
(giant	6–22	0.077–1.274	0.8–418 d	(0.0524)	Fressin et al. 2013[a])
'restricted' giant		0.077–0.3	0.8–418 d	0.0114	Fressin et al. 2013[a]
giant		0.1–0.3	418 d–10 yr	0.0388	Johnson–Cumming[b]
giant		0.3–15	2 d–10 yr	0.1339	Johnson–Cumming[b]

- occurrence around low-mass stars: Montet et al (2014)
- eccentricities: Beta distribution (Kipping 2013)
- low-mass planets: Fressin et al (2013)
- total numbers: 254 million planets around 260 million stars

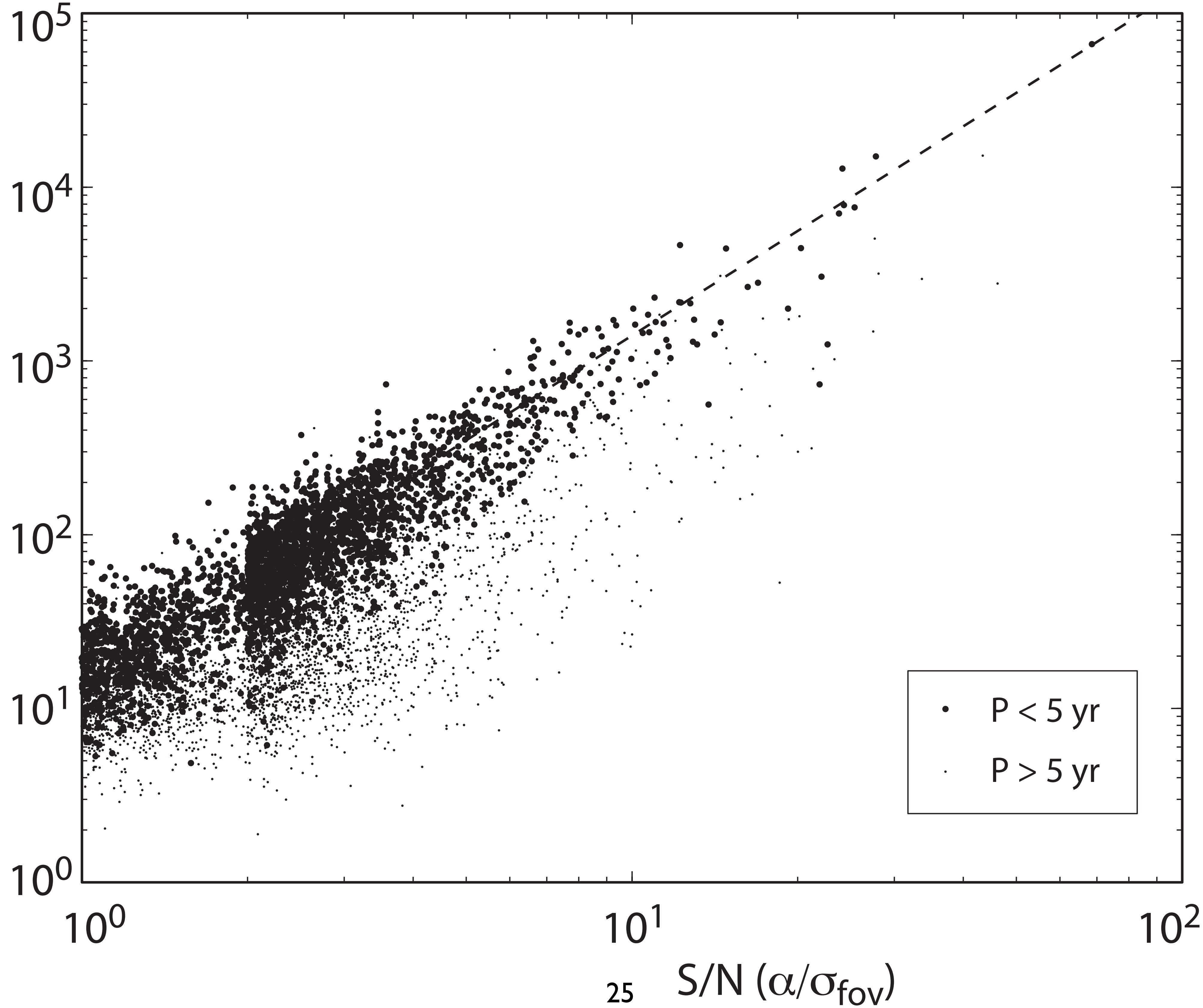
Detections vs S/N per field-of-view crossing

Δd (pc)	$N_\star^{\rm C08}$	$N_{\rm det}^{\rm C08}$	$N_\star$	$N_{\rm det}$ $\alpha > 0.5\,\sigma_{\rm fov}$	$N_{\rm tran}$ $\alpha > 0.5\,\sigma_{\rm fov}$	$N_{\rm det}$ $\alpha > 1\,\sigma_{\rm fov}$	$N_{\rm tran}$ $\alpha > 1\,\sigma_{\rm fov}$	$N_{\rm det}$ $\alpha > 2\,\sigma_{\rm fov}$	$N_{\rm tran}$ $\alpha > 2\,\sigma_{\rm fov}$	$N_{\rm det}$ $\alpha > 3\,\sigma_{\rm fov}$	$N_{\rm tran}$ $\alpha > 3\,\sigma_{\rm fov}$	$N_{\rm det}$ $\alpha > 6\,\sigma_{\rm fov}$	$N_{\rm tran}$ $\alpha > 6\,\sigma_{\rm fov}$
0– 50	10 000	1400	39 000	1508	5.4	897	2.8	512	1.4	359	0.9	186	0.4
50–100	51 000	2500	203 000	5914	20.6	3344	9.9	1789	4.4	1195	2.6	502	0.9
100–150	114 000	2600	476 000	8598	30.1	4877	14.3	2435	5.8	1466	3.0	452	0.7
150–200	295 000	2150	889 000	11737	37.2	6309	16.7	2851	6.2	1589	3.1	289	0.4
200–250	–	–	859 000	8976	26.9	4601	11.5	1860	3.8	862	1.5	51	0.0
250–300	–	–	1 298 000	11734	33.8	5677	13.5	2026	4.0	832	1.5	12	0.0
300–350	–	–	1 793 000	14972	42.2	6857	15.9	2008	3.8	636	1.0	–	–
350–400	–	–	1 775 000	13091	35.7	5464	12.4	1308	2.4	264	0.4	–	–
400–450	–	–	1 411 000	9019	24.3	3394	7.5	642	1.2	63	0.1	–	–
450–500	–	–	1 718 000	10439	27.3	3691	8.0	533	1.0	25	0.0	–	–
500–600	–	–	4 267 000	21172	53.8	6411	13.9	572	1.1	8	0.0	–	–
600–700	–	–	5 732 000	21286	53.7	4984	10.9	127	0.3	–	–	–	–
700–800	–	–	5 462 000	15434	37.9	2678	5.9	5	0.0	–	–	–	–
800–1400	–	–	36 500 000	35219	88.0	2083	4.7	–	–	–	–	–	–
Total	470 000	8750	62 000 000	189099	517	61267	148	16668	35	7299	14	1492	2

Properties of the detected planets



Detectability in terms of $\Delta\chi^2$



Our final estimates are then:

	$\Delta\chi^2$	$N_{\rm det}$	$N_{\rm tran}$	$N_{\rm det}$	$N_{\rm tran}$	$N_{\rm det}$	$N_{\rm tran}$	$N_{\rm det}$	$N_{\rm tran}$	$N_{\rm det}$	$N_{\rm tran}$
		$\alpha > 0.5\,\sigma_{\rm fov}$		$\alpha > 1\,\sigma_{\rm fov}$		$\alpha > 2\,\sigma_{\rm fov}$		$\alpha > 3\,\sigma_{\rm fov}$		$\alpha > 6\,\sigma_{\rm fov}$	
nominal 5-year mission	$>$ 30	**27505**	**42**	26038	42	12893	25	6541	12	1475	2
"	$>$ 50	**14806**	**25**	14755	25	10297	20	5762	10	1444	2
"	$>$100	6488	11	6488	11	6116	11	4393	8	1353	2
extended 10-year mission	$>$ 30	**90751**	**135**	58674	117	16666	35	7299	14	1492	2
"	$>$ 50	**53015**	**82**	47630	80	16648	35	7299	14	1492	2
"	$>$100	25958	39	25882	39	15836	30	7285	14	1492	2

…estimating detectability from the S/N per field-of-view crossing is a simplistic approach not taking into account:

- the number of observations
- the distribution of projection geometries on the sky
- the orbit period, etc

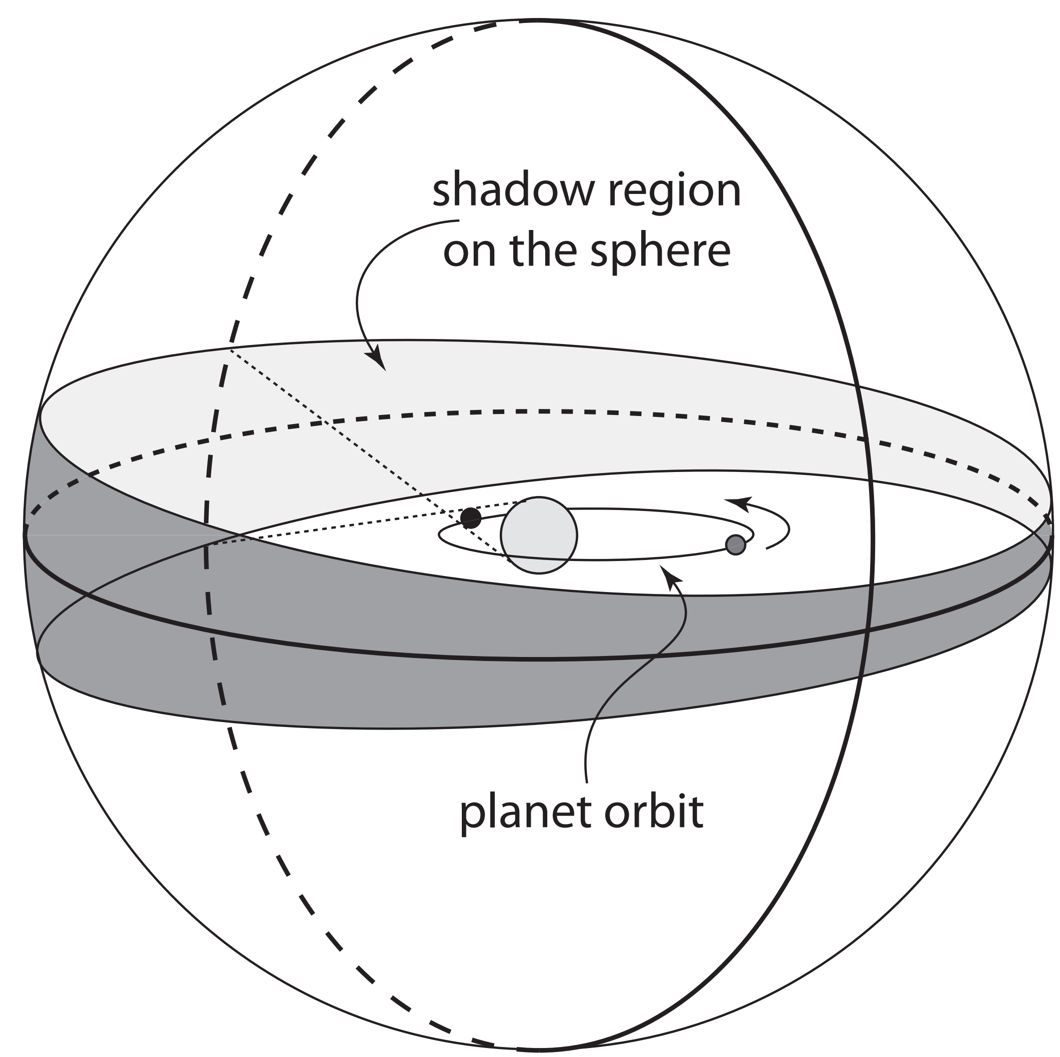
How many of these are transiting?

- probability given by the solid angle
- for circular orbits (e.g. Borucki & Summers 1984):

$$p = \frac{R_\star}{a_\mathrm{p}} \simeq 0.005 \left(\frac{R_\star}{R_\odot}\right) \left(\frac{a_\mathrm{p}}{1\ \mathrm{AU}}\right)^{-1}$$

- for eccentric orbits (.e.g Barnes 2007):

$$p = \left(\frac{R_\star + R_\mathrm{p}}{a_\mathrm{p}}\right) \left(\frac{1}{1-e^2}\right)$$



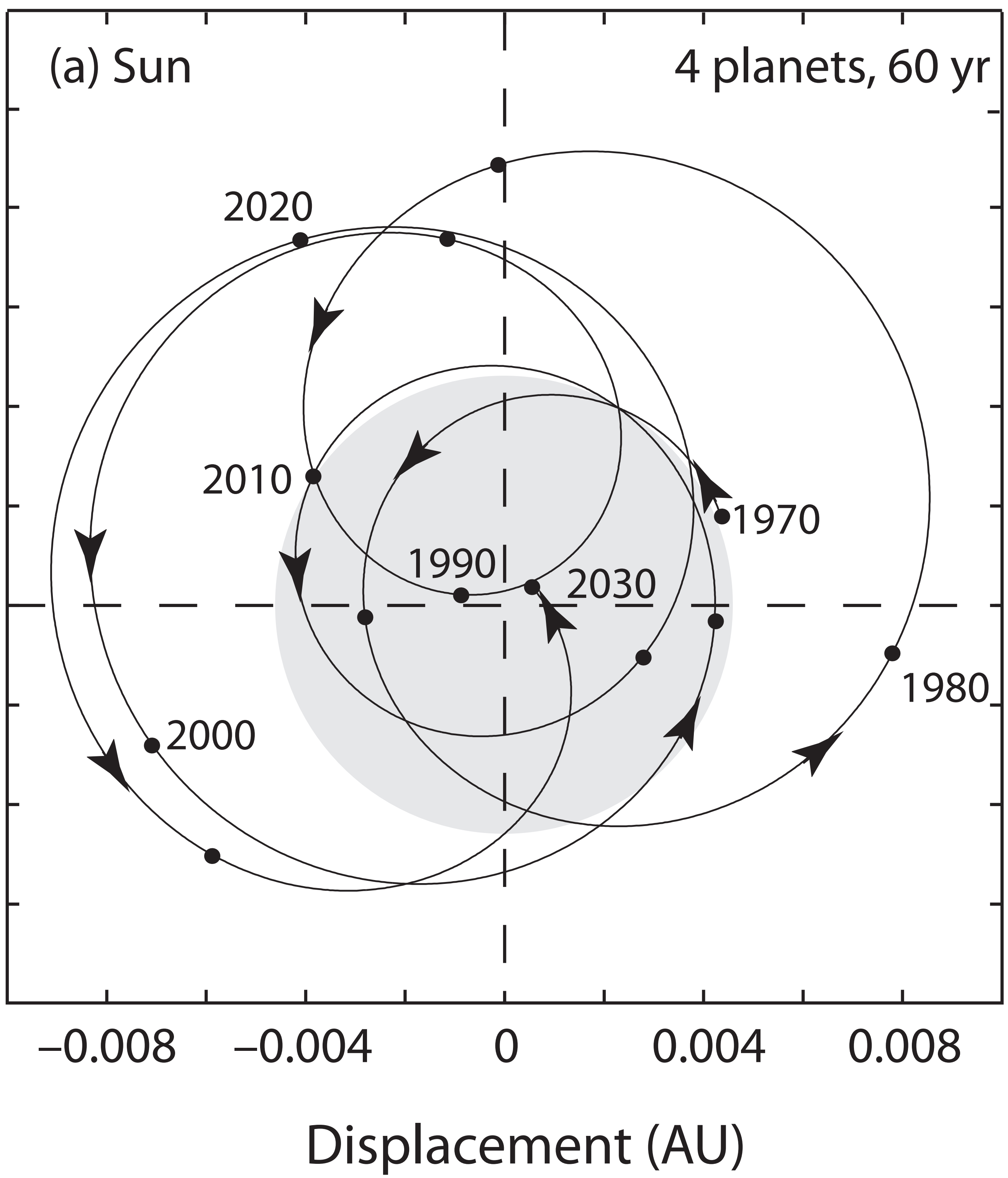
There will be ~40 transiting planets

- periods: 1-5 years, i.e. ‘middle region’ planets
- ~1-2 M_J, so (bright star) transits pronounced
- some may be in the Gaia photometry
- some may be in existing transit databases
- interesting for amateur/citizen science
- will allow characterisation of a type of planet poorly characterised by other means

Multiple (massive) planets

Astrometric motion for multiple planets...

(assuming orbits are co-planar)

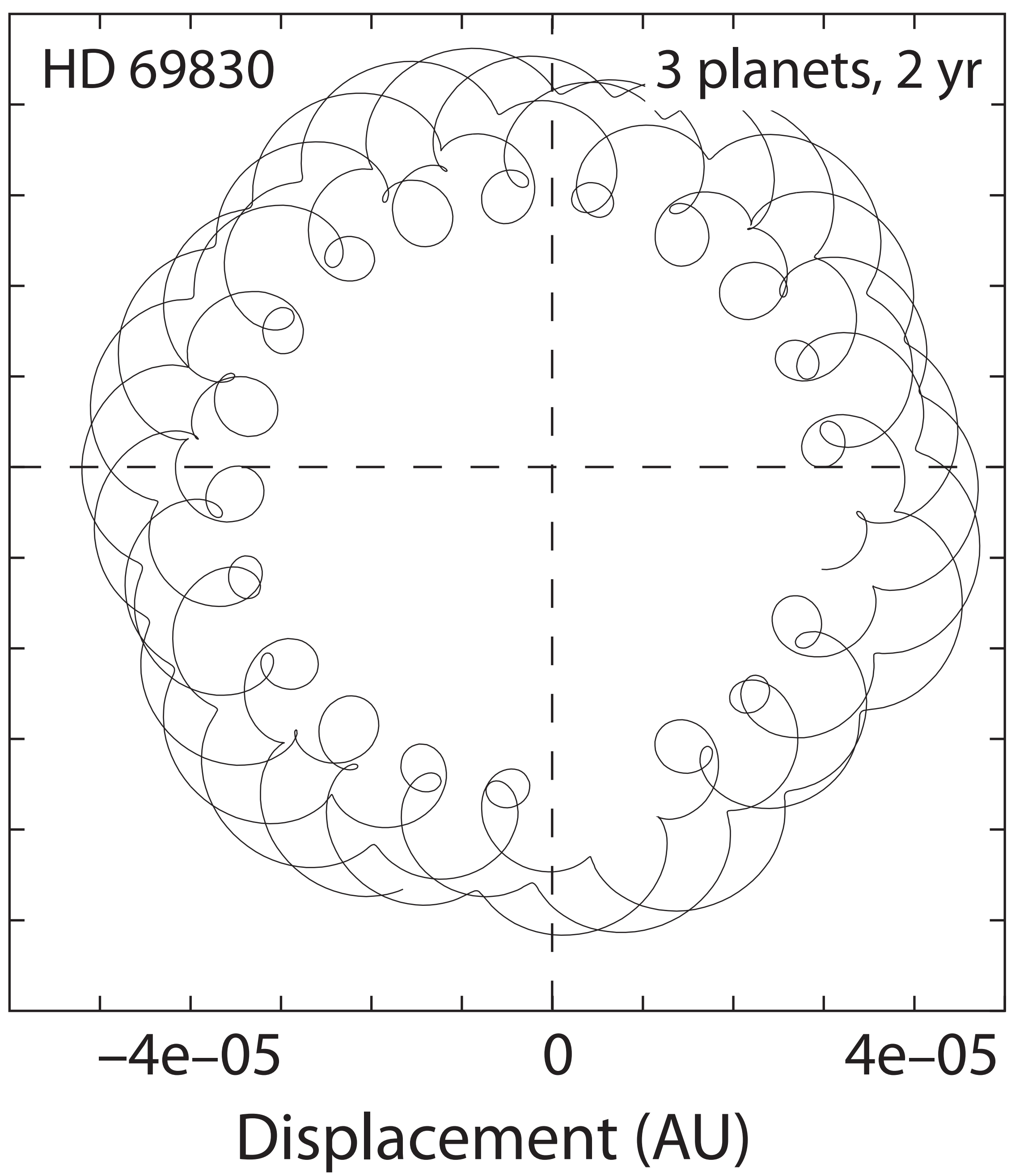


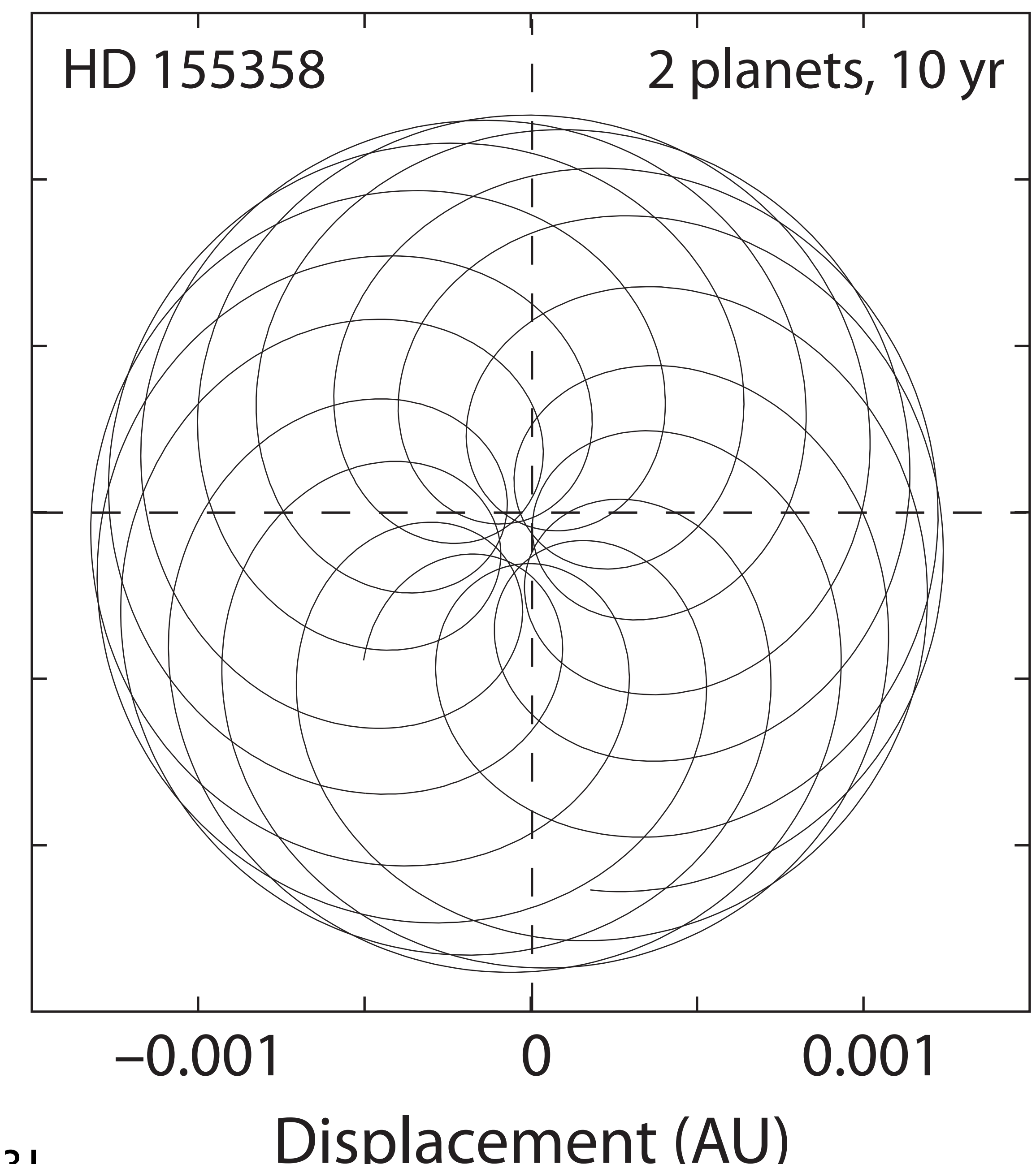
The sun's motion guides us:

- Newton: *'since that centre of gravity is continually at rest, the Sun, according to the various positions of the planets, must continuously move every way, but will never recede far from that centre' (Cajori 1934)*
- barycentre frequently extends beyond the solar disk
- periods when the Sun's motion is 'retrograde' with respect to the barycentre (~1990, 1811,1632)

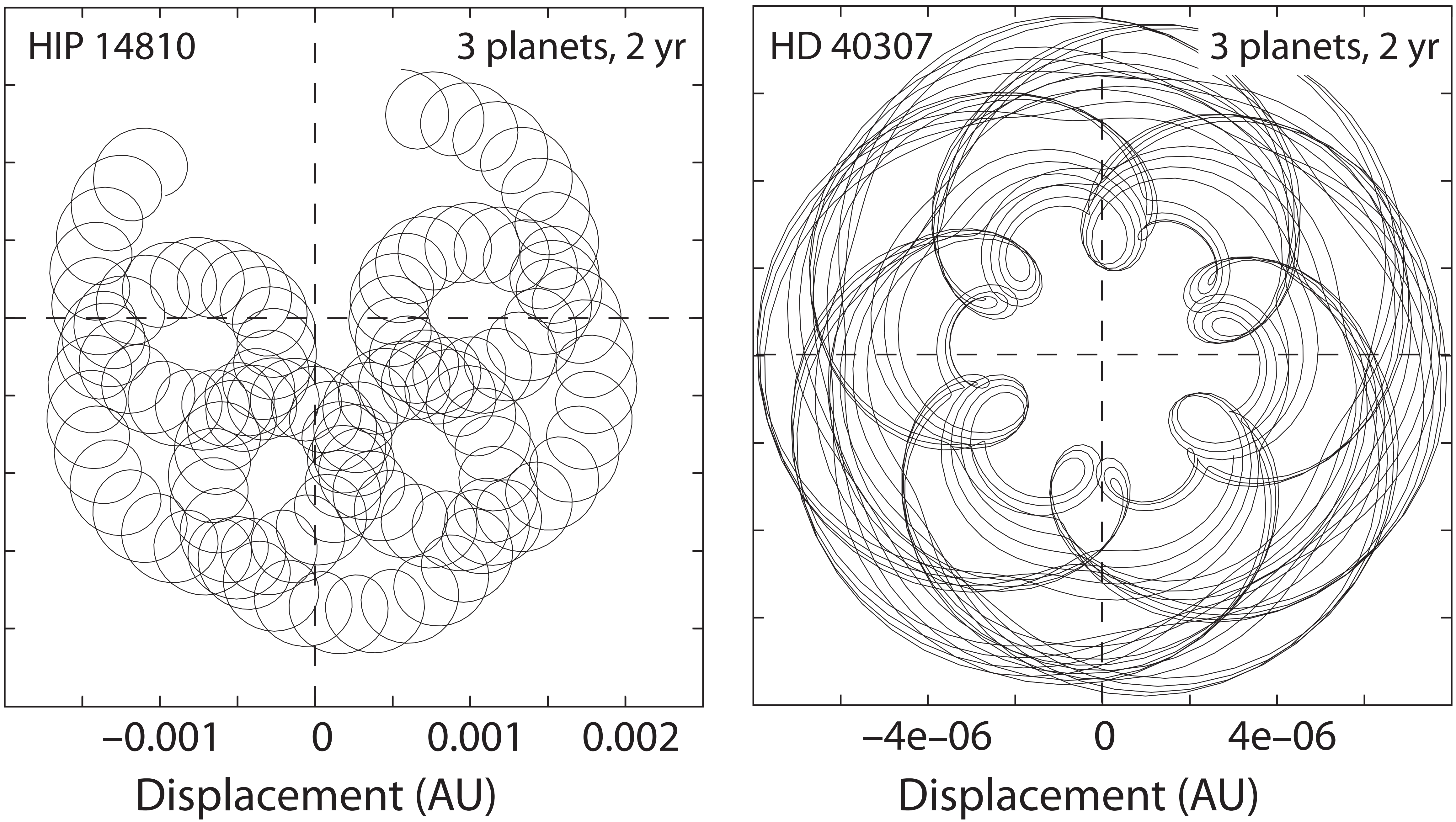
Motion of host star around barycentre for multiple exoplanets

(assuming coplanarity)

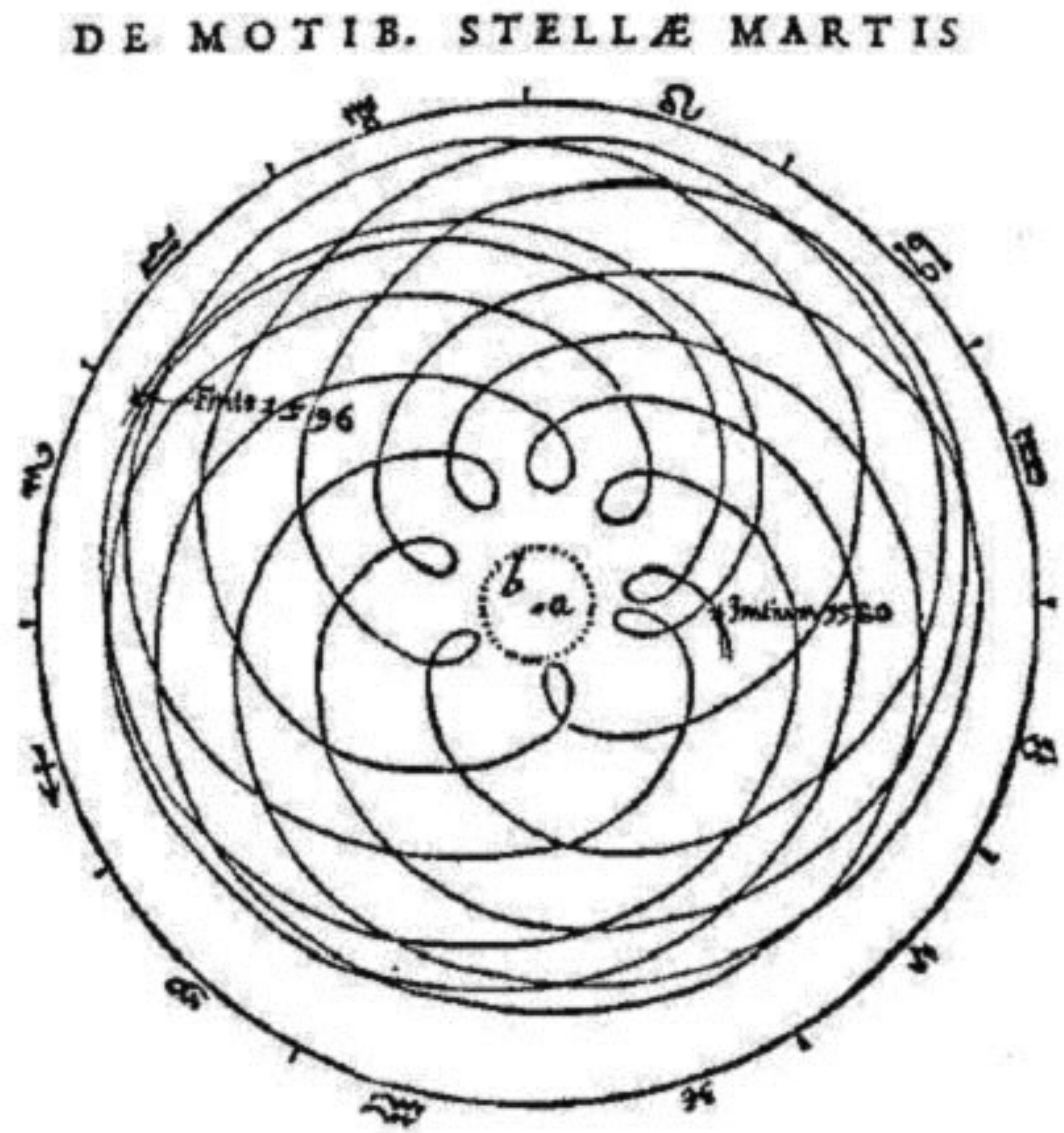




Motion for multiple planets (cont.)



Astronomia Nova (1609) includes Kepler's hand drawing of the orbit of Mars viewed from Earth



...designated as 'mandala'
(Sanskrit for circle)
by Wolfram (2010)

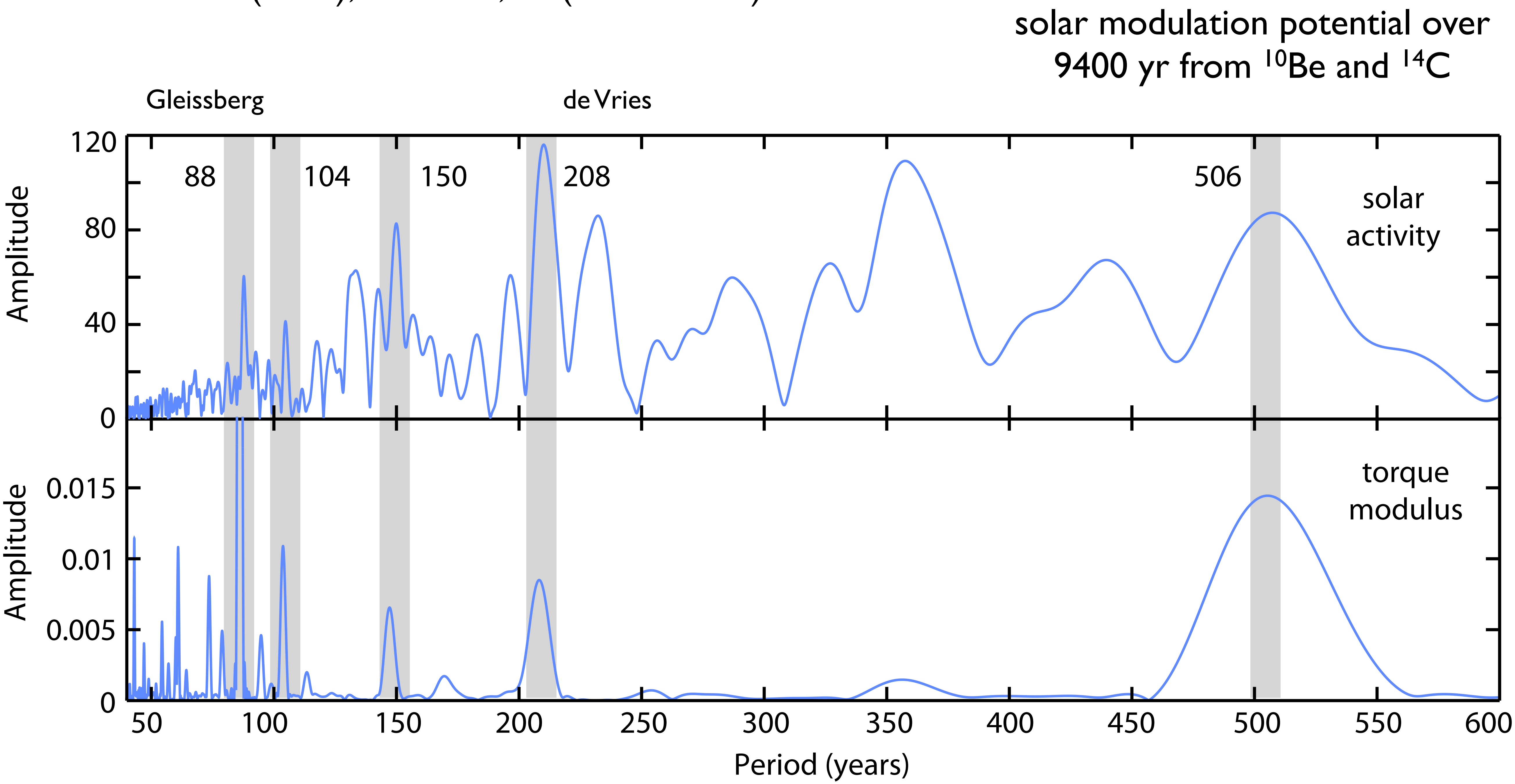
Exoplanets and the solar dynamo

Now for something contentious...

- solar axial rotation is invoked in models of the solar cycle (e.g. turbulent dynamo operating in or below the convection envelope)
- precise nature of the dynamo, and details of associated solar activity (sun spot cycles, and the prolonged Maunder-type solar minima) are unexplained
- empirical investigations have long pointed to a link between the Sun's barycentric motion and various solar variability indices (e.g. Wolf, 1859; Brown, 1900; Schuster, 1911; Jose, 1965; Ferris, 1969), specifically:
  - the Wolf sun spot number counts (Wood & Wood, 1965)
  - climatic changes (Mörth & Schlamminger, 1979; Scafetta, 2010)
  - the 80-90-yr secular Gleissberg cycles (Landscheidt, 1981, 1999)
  - prolonged Maunder-type minima (Fairbridge & Shirley, 1987; Charvátová, 1990, 2000)
  - short-term variations in solar luminosity (Sperber et al., 1990)
  - sun spot extrema (Landscheidt, 1999)
  - the 2400-yr cycle seen in 14C tree-ring proxies (Charvátová, 2000)
  - hemispheric sun spot asymmetry (Juckett, 2000)
  - torsional oscillations in long-term sun spot clustering (Juckett, 2003)
  - violations of the Gnevishev–Ohl sun spot rule (Javaraiah, 2005)

Just one example...

Abreu et al (2012), A&A 548, 88 (ETH Zürich)



Proposed coupling mechanisms between the solar axial rotation and orbital revolution:

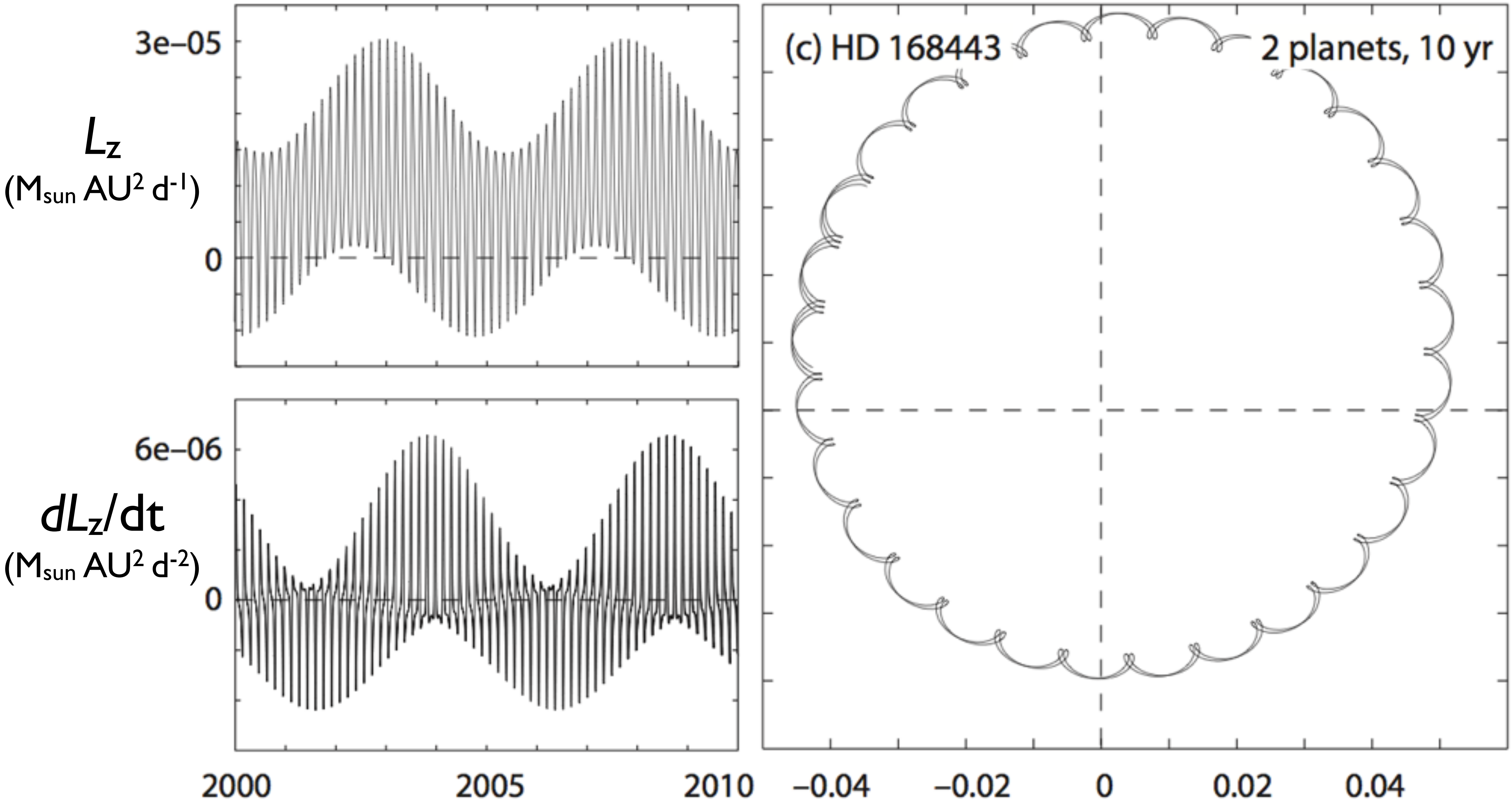
- Zaqarashvili (1997), Juckett (2000), contested by Shirley (2006)
- Abreu (2012): time-dependent torque exerted by the planets on a non-spherical tachocline
- Callebaut & de Jager (2012): effect considered as negligible

Exoplanets can arbitrate

(Perryman & Schulze-Hartung 2011)

- behaviour cited as correlated with the Sun's activity includes
  - changes in orbital angular momentum, $\mathrm{d}L/\mathrm{d}t$
  - intervals of negative orbital angular momentum
- these are common (but more extreme) in exoplanet systems
- HD 168443 and HD 74156 have $\mathrm{d}L/\mathrm{d}t$ exceeding that of the Sun by more than 10^5
- activity monitoring should therefore offer an independent test of the hypothetical link between:
  - the Sun's barycentric motion
  - and the many manifestations of solar activity

HD 168433



- two massive planets (8−18M_J) at 0.3−3 AU, e_1~0.5
- most extreme negative L_z and largest dL/dt
- periodicity of ~58 days

Summary

- accurate distances:
  - calibration of host star parameters, including R for transiting
  - calibration of asteroseismology models
- accurate proper motions: Galactic dynamics and population
- multi-epoch high-accuracy photometry:
  - new transiting systems (several hundred?)
  - calibration of photometric jitter vs spectral type
- multi-epoch astrometry:
  - discovery of new (massive, long-period) planets (7,000−17,000)
  - co-planarity of systems: evolutionary models
  - position angle of planet transits (some multiple?)

End